

Observational Effects of Strong Gravity in Vicinity of Supermassive Black Holes

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Here we discuss the effects of strong gravity that can be observed in electromagnetic spectra of active galactic nuclei (AGN). According to the unification model of an AGN, there is a supermassive black hole ($10^7 - 10^9 M_\odot$) in its center, surrounded by an accretion disk that radiates in the X-ray band. Accretion disks could have different forms, dimensions, and emission, depending on the type of central black hole (BH), whether it is rotating (Kerr metric) or nonrotating (Schwarzschild metric). We modeled the emission of an accretion disk around supermassive BH using numerical simulations based on a ray-tracing method in the Kerr metric. A broad emission line Fe K α at 6.4 keV with asymmetric profile (narrow bright blue peak and a wide faint red wing) has been observed in a number of type 1 AGN. The effects of strong gravitational field are investigated by comparison between the modeled and observed iron K α line profiles. The results of our modeling show that the parameters of the Fe K α line emitting region have significant influence on the line profile and thus, allow us to determine the space-time geometry (metric) in vicinity of the central BH of AGN, and also can give us information about the plasma conditions in these regions.

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1 Introduction

It is now widely accepted that AGN derive their extraordinary luminosities (sometimes more than 10^4 times higher than luminosities of "ordinary" galaxies) from energy release by matter accreting towards, and falling into, a central supermassive BH. The accretion disks around the central BH represent an efficient mechanism for extracting gravitational potential energy and converting it into radiation, giving us the most probable explanation for the main characteristics of AGN (high luminosity, compactness, jet formation, rapid time variation in radiation and the profile of the Fe K α spectral line). Thus, AGN are powerful sources of radiation in a wide spectral range: from γ rays to radio waves [1].

The most important feature of the X-ray radiation of AGN (which is generated in the innermost region around a central BH) is a broad emission line Fe K α at 6.4 keV that may have an asymmetric profile (narrow bright blue peak and wide faint red peak). It was discovered in Seyfert 1 galaxy MCG-6-30-15 [2] and later on observed in a number of AGN. In some cases the line width corresponds to one third of speed of light, indicating that its emitters rotate with relativistic velocities. Therefore, the line is probably produced in a very compact region near the central BH of AGN and can provide us some essential information about the plasma conditions and the space-time geometry in vicinity of the BH [3].

Black holes have only three measurable parameters (not including the Hawking temperature): charge, mass and angular momentum [4]. In this paper we will pay attention mostly to angular momentum or spin of central supermassive BH of AGN, which is a property of the space-time metric.

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2 Numerical simulations

An accretion disk could have different forms, dimensions and emissivity, depending on the type of its central BH, whether it is rotating (Kerr metric) or nonrotating (Schwarzschild metric). We modeled emission of an accretion disk around supermassive BH using numerical simulations based on a ray-tracing method in a Kerr metric, taking into account only photon trajectories reaching the observer's sky plane in the infinity [3, 5, 6]. Using this method we are able to obtain colorful images of accretion disk as would be seen by a distant observer with powerful high-resolution telescope (see left panels of Figs. 1 - 3). From such disk images we then calculate total observed flux F_{obs} according to the following expression:

$$F_{obs}(E_{obs}) = \int_{image} \epsilon(r) g^4 \delta(E_{obs} - gE_0) d\Xi, \quad (1)$$

where $\epsilon(r)$ is the disk emissivity, E_0 is the line transition energy ($E_0^{Fe K\alpha} = 6.4$ keV), $g = E_{obs}/E_{em}$ is the energy shift due to relativistic effects (E_{obs} is the observed energy and E_{em} is the emitted energy from the disk) and $d\Xi$ is solid angle subtended by the accretion disk on observer's sky. The modeled line profile is then obtained by binning the flux into the energy shift (g) axis (see right panels of Figs. 1 - 3). The iron $K\alpha$ line shape strongly depends on emissivity law of the disk $\epsilon(r)$, so we assume the standard Shakura-Sunyaev disk model [7], where accretion occurs via an optically thick and geometrically thin disk.

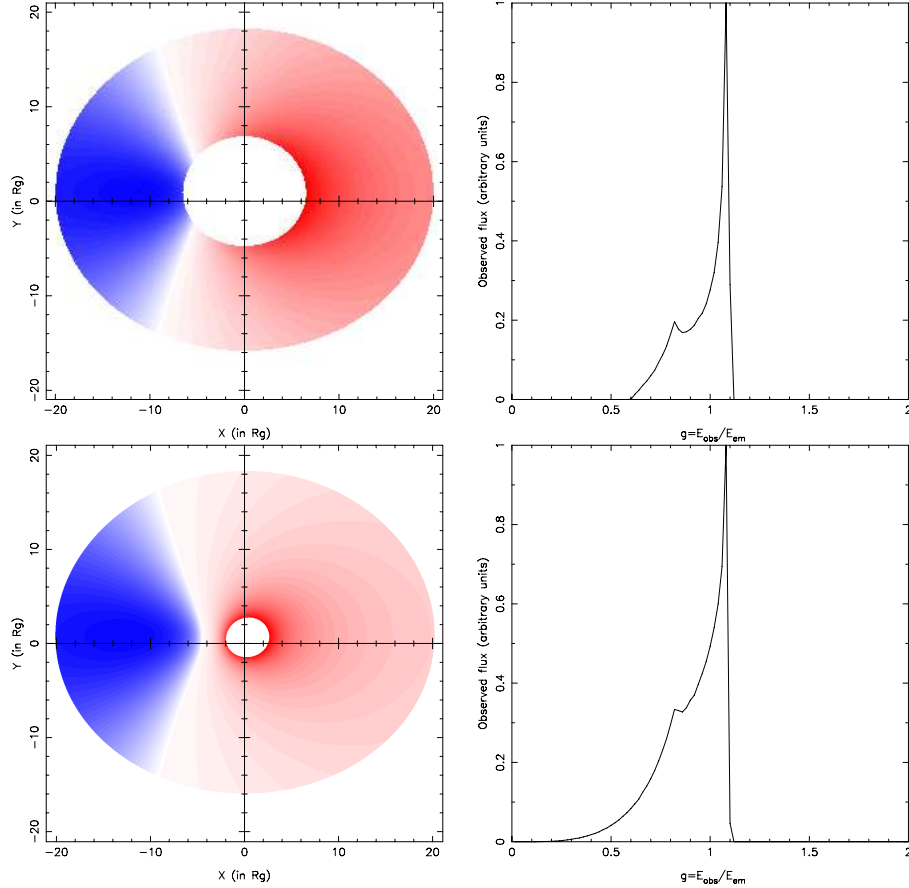


Fig. 1 Illustrations of accretion disk (left) and the corresponding Fe $K\alpha$ line profiles (right) in the case of Schwarzschild (top) and Kerr metric with angular momentum parameter $a = 0.998$ (bottom). The disk inclination is $i = 35^\circ$ and its inner and outer radii are $R_{in} = R_{ms}$ and $R_{out} = 20 R_g$, respectively.

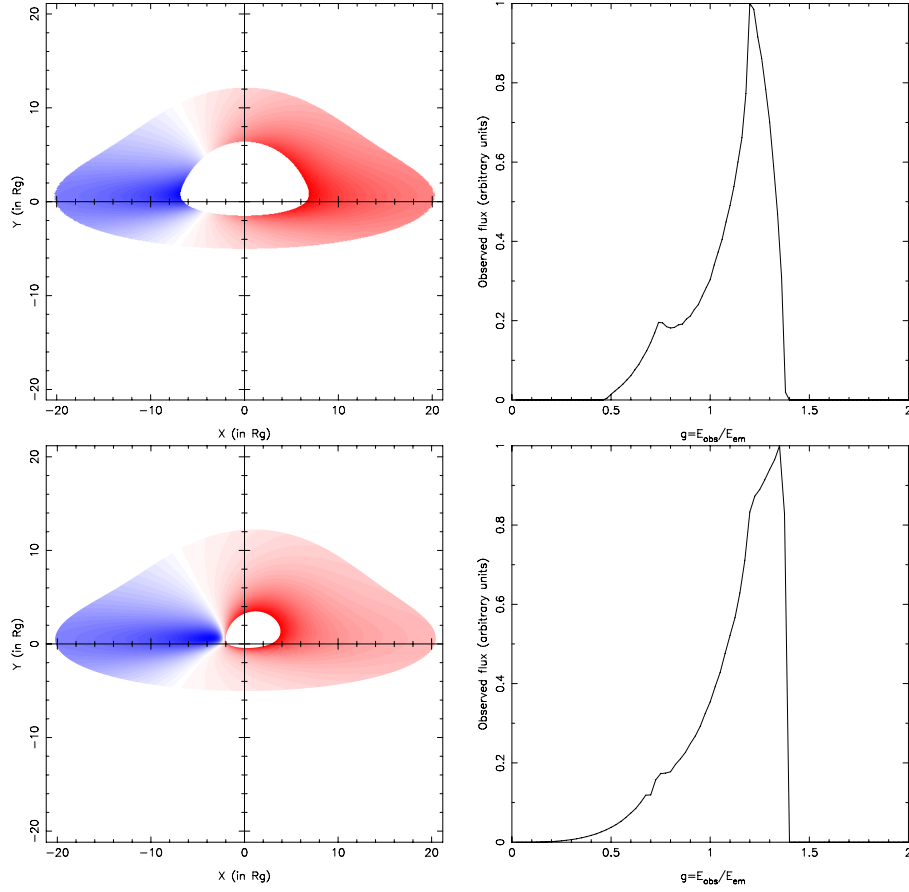


Fig. 2 The same as in Fig. 1 but for a highly inclined disk with $i = 75^\circ$.

3 Results

The effects of strong gravitational field on the Fe $K\alpha$ line profile have been investigated in order to compare the modeled and observed line profiles. To obtain modeled line profiles, it is necessary to define a number of parameters which describe the line emitting region in the disk, such as constraints for its size, the disk inclination angle, the mass of the central BH and its angular momentum. For the disk inclination we adopted the averaged value from the study of the Fe $K\alpha$ line profiles of 18 Seyfert 1 galaxies: $i = 35^\circ$ (see [8] and references therein). The inner radius R_{in} of the disk can not be smaller than the radius of the marginally stable orbit R_{ms} , that corresponds to $R_{ms} = 6R_g$ (gravitational radius $R_g = GM/c^2$, where G is gravitational constant, M is the mass of central BH, and c is the velocity of light) in the Schwarzschild metric and to $R_{ms} = 1.23R_g$ in the case of the Kerr metric with angular momentum parameter $a = 0.998$. To select the outer radius R_{out} of the disk, we take into account some recent investigations of the Fe $K\alpha$ line profile showing that it should be emitted from the innermost part of the disk which outer radius is within several tens of R_g (see [8] and references therein).

In order to study observational effects of strong gravity in vicinity of supermassive BH in the center of AGN, we analyzed three cases for the Fe $K\alpha$ line emitting region: (i) $R_{in} = R_{ms}$, $R_{out} = 20 R_g$ and $i = 35^\circ$ (in both Schwarzschild and Kerr metric), (ii) $R_{in} = R_{ms}$, $R_{out} = 20 R_g$ and $i = 75^\circ$ (in both Schwarzschild and Kerr metric) and (iii) $i = 75^\circ$ and the line emitting region in Kerr metric with $a = 0.998$ is in form of narrow annulus with width $= 1R_g$, located between: (iiia) $R_{in} = 10 R_g$ and $R_{out} = 11 R_g$, (iiib) $R_{in} = 30 R_g$ and $R_{out} = 31 R_g$ and (iiic) $R_{in} = 50 R_g$ and $R_{out} = 51 R_g$.

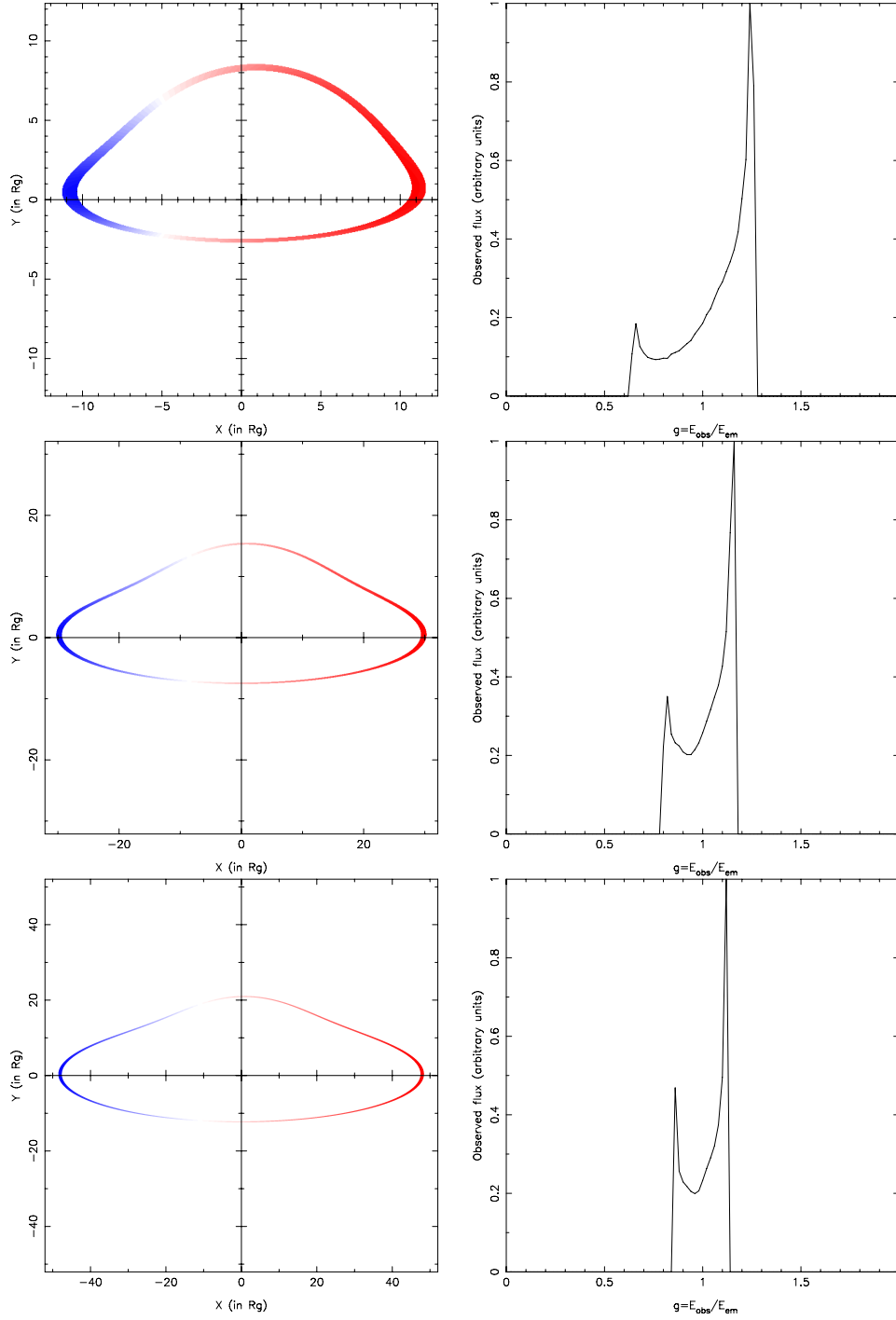


Fig. 3 The same as in Fig. 2 but for the Fe K α line emitting region in form of narrow annulus with width = $1R_g$, extending from: $R_{\text{in}} = 10 R_g$ to $R_{\text{out}} = 11 R_g$ (top), $R_{\text{in}} = 30 R_g$ to $R_{\text{out}} = 31 R_g$ (middle) and $R_{\text{in}} = 50 R_g$ to $R_{\text{out}} = 51 R_g$ (bottom).

Illustrations of an accretion disk and the corresponding Fe K α line shapes in the first case for Schwarzschild and Kerr metric are presented in Fig. 1. As one can see in Fig. 1, the red peak of the Fe K α line

is brighter in case of almost maximally rotating BH, but at the same time it is also more embedded into the blue peak wing and therefore less separable from it. Consequently, angular momentum of the central BH has significant influence on the line shape which supports assumption that the line originates from the innermost part of accretion disk, close to the central BH. This fact can be used for estimation of angular momentum of central BH in observed AGN (see e.g. [2]).

Fig. 2 contains illustrations of the line emitting regions and the corresponding line shapes in the case of highly inclined disk ($i = 75^\circ$). Here, the line profiles are broader than in the first case, mostly due to higher inclination. As it can be seen in Fig. 2, in case of Kerr metric, the red peak of the line is again more embedded into its blue peak wing (as in the first case) and it confirms that this effect can be most likely attributed to angular momentum.

Results for the third analyzed case are presented in Fig. 3. From this figure one can see how the Fe $K\alpha$ line profile is changing as the function of distance from central BH. When the line emitters are located at the lower radii of the disk, i.e. closer to the central BH, the lines are broader and the line profiles are more asymmetric (see Fig. 3). If the line emission is originating at larger distances from the BH, the red peak of the line becomes brighter and line profile narrower and more symmetric. In majority of AGN, where the broad Fe $K\alpha$ line is observed¹, its profile is more similar to the modeled profile as obtained under assumption that the line emitters are located close to the central BH. Therefore, comparisons between the observed and modeled Fe $K\alpha$ line profiles can bring us some essential information about strong gravitational field in vicinity of central supermassive BH of AGN.

4 Conclusions

We performed numerical simulations based on a ray-tracing method in a Kerr metric in order to model the emission of accretion disk around supermassive BH of AGN. We also simulated the influence of a strong gravitational field on the Fe $K\alpha$ line, showing that these effects can be detected in the observed line shapes. According to the obtained results, angular momentum or spin of central supermassive BH of AGN has significant influence on the line profile. Therefore, the analysis of the high resolution observations of the Fe $K\alpha$ line could be used for determination of the space-time geometry (metric) in vicinity of the supermassive BH, supposed to be in heart of AGN.

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¹ Note here that in some AGN only the narrow Fe $K\alpha$ line is observed, but it is supposed to be emitted in the disk corona that is located farther from the disk, and therefore, these relativistic effects cannot be detected in the line profile